



How do climatic and management factors affect agricultural ecosystem services? A case study in the agro-pastoral transitional zone of northern China



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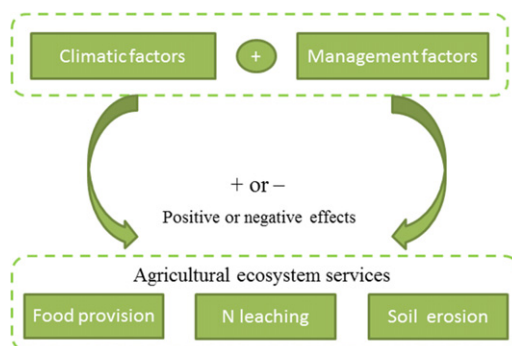
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HIGHLIGHTS

- Management factors had larger effects on AES than climatic factors.
- Daily minimum temperature was the main climatic factor affecting changes in AES.
- Tradeoffs existed between crop production and negative environmental effects.
- Agro-ecosystem can be more sustainable through adaptive management practices.

GRAPHICAL ABSTRACT



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ABSTRACT

Agricultural ecosystem management needs to ensure food production and minimize soil erosion and nitrogen (N) leaching under climate change and increasingly intensive human activity. Thus, the mechanisms through which climatic and management factors affect crop production, soil erosion, and N leaching must be understood in order to ensure food security and sustainable agricultural development. In this study, we adopted the GIS-based Environmental Policy Integrated Climate (EPIC) model to simulate crop production, soil erosion, and N leaching, and used a partial least squares regression model to evaluate the contributions of climate variables (solar radiation, precipitation, wind speed, relative humidity, and maximum and minimum temperature) and management factors (irrigation, fertilization, and crop cultivation area) on agricultural ecosystem services (AES) in the agro-pastoral transitional zone (APTZ) of northern China. The results indicated that crop production and N leaching markedly increased, whereas soil erosion declined from 1980 to 2010 in the APTZ. Management factors had larger effects on the AES than climate change. Among the climatic variables, daily minimum temperature was the most important contributor to the variations in ecosystem services of wheat, maize, and rice. Spatial changes in the cultivated area most affected crop production, soil erosion, and N leaching for majority of the cultivated areas of the three crops, except for the wheat-cultivated area, where the dominant factor for N leaching was fertilization. Although a tradeoff existed between crop production and negative

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environmental effects, compromises were possible. These findings provide new insights into the effects of climatic and management factors on AES, and have practical implications for improving crop production while minimizing negative environmental impacts.

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1. Introduction

The global agricultural ecosystem, representing humankind's largest engineered ecosystem, occupies about 38% of the earth's terrestrial surface (FAOSTAT, 2011). This ecosystem can supply multiple ecosystem services, such as provision (i.e., food and fiber), support (i.e., nutrient cycling), culture (i.e., recreation and spiritual), and regulation (pollination), which are essential for human well-being and sustainable development (MA, 2005; Wu, 2013).

Among the different agricultural ecosystem services, food provision usually receives special attention due to the need to maintain regional food security (FAO, 2015). Although global food production has increased rapidly in the past decades, and food security status has improved, approximately 795 million people were still undernourished worldwide in 2015 according to the Food and Agriculture Organization (FAO) report (FAO, 2015). By the middle of the current century, the global population is expected to increase to 9 billion (Godfray et al., 2010), and this rapid population growth will present new challenges for food production.

This urgent requirement for food production will increase agricultural land-use intensity and have non-negligible effects on the environment (Basche et al., 2016; Foley et al., 2005; Liu et al., 2016). Agricultural practices may have negative environmental effects, such as soil erosion (Montgomery, 2007), N leaching (Valkama et al., 2016), and habitat degradation, and thus, present a threat to sustainable agricultural ecosystem management. Agricultural production is sensitive to climate change, which may further intensify the negative environmental effects of soil erosion and N leaching. Therefore, there is an urgent need to characterize the spatial and temporal variation in crop production, soil erosion, and N leaching in order to target measures of adaptation to climate change.

Human-induced changes in management practices (i.e., fertilization, irrigation, and adjustment of crop cultivation structure) are prominent factors leading to variation in agricultural ecosystem services (AES) (Berzsenyi et al., 2000; Zhang et al., 2017; Zhu and Chen, 2002). Numerous studies have evaluated the effects of fertilization, irrigation, and climate change on AES using control variable methods. Gheysari et al. (2009) evaluated the effects of different irrigation and nitrogen fertilizer levels on N leaching, and found that N leaching could be controlled with an appropriate combination of fertilizer and irrigation management. Liu et al. (2007) analyzed the effects of irrigation on crop production and found it to play an important role in increasing food production in China. Yin et al. (2015) projected the potential yield of major crops under climate change, in which the crop distribution was held as static.

However, few studies have evaluated the contributions of both climatic and management factors on variations in AES. In particular, the contribution of changes in crop distribution to variation in AES is rarely been considered. In practice, the driving factors of climatic change and management factors were combined together to play role in the variation in AES. Therefore, understanding the integrated contributions of driving factors to the variation in AES and quantifying the predominant factors are necessary to optimize the AES under climate change conditions.

It is necessary to understand the mechanisms of interactions among multifaceted AES. Therefore, we selected the arid and semiarid agro-pastoral transitional zone (APTZ) of northern China as the study area and integrated the GIS-based Environmental Policy Integrated Climate (EPIC) model and partial least square regression model to identify how climate change and human management factors affect AES. Our objectives were to 1) analyze trends in driving factors, including the

climatic variables of solar radiation, precipitation, minimum temperature ($T_{\min}$), maximum temperature ($T_{\max}$), wind speed, and relative humidity, and human management measures, including fertilization, irrigation, and adjustment of cultivated area of wheat, maize, and rice from 1980 to 2010; 2) simulate crop production, soil erosion, and N leaching in wheat, maize, and rice from 1980 to 2010; and 3) evaluate the respective contributions of these driving factors to the variation in AES, and to select the factor with the largest effect on the AES.

2. Study area

The APTZ is located between the 34°46'–48°32'N and 100°55'–124°41'E and covers an area of approximately $7.26 \times 10^5 \text{ km}^2$ (Fig. 1). Although the cropland area has changed significantly since the implementation of the Grain for Green project in 1999 (i.e., returning the farmland to forest or grassland), the APTZ remains an important area for food provision, and accounted for 7.7% of China's total food production in 2010 (China Agricultural Statistical Yearbook, 2010). The APTZ is located in the arid and semiarid region, which has a temperate continental monsoon climate with strong winds, cold weather, and little rain. From 1980 to 2010, the average annual temperature was unevenly distributed and varied from 3.0 to 9.9 °C (Fig. 1a). The spatial distribution of precipitation is extremely uneven across the whole region. The areas with the most precipitation are concentrated in the northeast and southwest, where the average annual precipitation is over 500 mm, whereas the average annual precipitation in the dry areas is <250 mm (Fig. 1b). Limited irrigation facilities have been developed to ensure local agricultural production, which is mainly distributed in the northeast and southwest regions (Fig. 1c). The terrain slope in this region ranges from 0 to 38% (Fig. 1d). The main soil types are loam and sand, accounting for 74.9% of the whole study area (Fig. 1e).

3. Materials and methods

3.1. Model description

EPIC is a cropping system model that has been widely used since 1990 (Sharpley and Williams, 1990), and is an effective tool for assessing the effect of agricultural management measures on crop yield and associated biophysical processes (Benson et al., 1992; Chavas et al., 2009; Thomson et al., 2006). The EPIC model consists of a crop growth module, a soil erosion module, a nutrient cycling module, and other modules. In the present study, the EPIC model (version 0509) was combined with ArcGIS 10.1 to simulate the AES of crop production, soil erosion, and N leaching for wheat, maize, and rice in the crop-cultivated areas. In the calibration process, the simulated yield of each grid within a municipal area was averaged to match the statistical yield recorded at the municipal scale. The linear root mean square error (RMSE) and relative RMSE (RRMSE) indicators were used to evaluate the performance of EPIC in simulating crop yield.

3.1.1. Crop growth module

In the EPIC model, the daily increase in potential biomass is calculated using the algorithm described by Monteith (1977):

$$\Delta B_{p,i} = 0.001 \times WA \times PAR_i \quad (1)$$

where $\Delta B_{p,i}$ represents the increased potential biomass in day i , WA is the efficiency of light energy utilization, and PAR_i is the intercepted

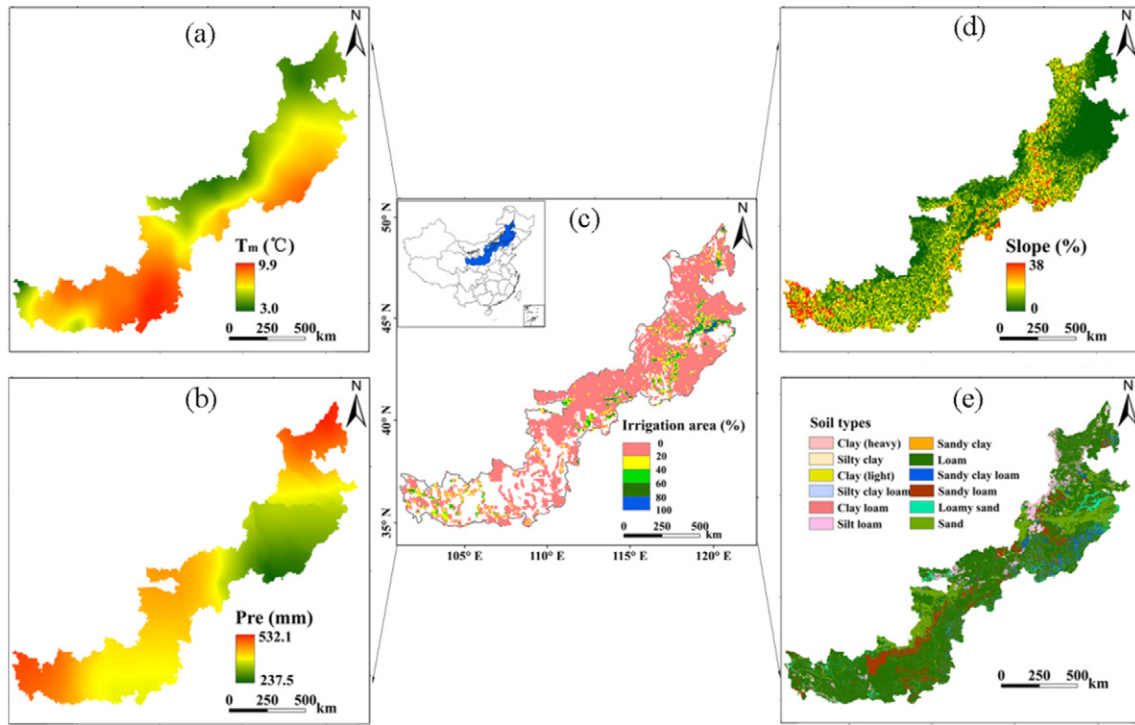


Fig. 1. The location of agro-pastoral transitional zone (APTZ) in northern China, average annual temperature (T_m) from 1980 to 2010 (a), average annual precipitation (Pre) from 1980 to 2010 (b), irrigation area (c), slope (d), and soil types (e).

photosynthetic active radiation. PAR can be estimated using Beer's law equation, as follows (MONSI, 1953):

$$PAR_i = 0.5RA_i(1 - e^{-0.65LAI_i}) \quad (2)$$

where RA represents the solar radiation, and LAI is the leaf area index.

In the presence of environmental stress, the actual daily increase in biomass can be calculated using the following equation:

$$\Delta B_{a,i} = \Delta B_{p,i} S_{reg,i} \quad (3)$$

where $\Delta B_{a,i}$ represents the actual increased biomass in day i , and $S_{reg,i}$ is the regulation factor, which is the minimum of the stress factors at day i .

Then, crop yield is calculated with the following equation:

$$Yield = HIA \times \sum_{i=1}^n \Delta B_{a,i} \quad (4)$$

where $Yield$ is the harvest dry yield, HIA is the adjusted harvest index under water stress, and n is the number of days from the planting date to the maturity date.

3.1.2. Soil erosion module

The soil erosion module in the EPIC model includes water erosion and wind erosion. The water erosion caused by rainfall and runoff is calculated with the modified USLE Eqs. (5) and (6) (Onstad and Foster, 1975). The soil erosion caused by irrigation is calculated with the MUSLE Eq. (7) (Williams, 1975). The equations are as follows:

$$Y_1 = x(K)(CE)(PE)(LS)(ROKF) \quad (5)$$

$$x = 0.646EI + 0.45(Q \cdot q_p)^{0.33} \quad (6)$$

$$Y_2 = 11.8(Q \cdot q_p)^{0.56} (K)(CE)(PE)(LS) \quad (7)$$

where Y_1 is the water erosion yield caused by rainfall and runoff, Y_2 is the water erosion caused by irrigation, x is the rainfall and runoff erosivity factor, K is the soil erosion factor, CE is the crop management factor [the minimum value here of CE was 0.47, which is representative of the main crops in APTZ (Zhang et al., 2008)], PE is the erosion control practice factor [a constant value of 0.01 was set for paddy fields and a constant value of 0.4 was set for other fields (Li et al., 2011)], L is the slope length factor, S stands for the steepness factors, $ROKF$ is the coarse fragment factor, EI is the rainfall energy factor, Q^* stands for the runoff volume, and q_p^* represents the peak runoff rate.

Wind erosion in the EPIC model is calculated by the modified wind erosion equation (Cole et al., 1983). The lower limit of erosive wind velocity for the APTZ is 5 m s^{-1} (Guo et al., 2012). In this study, the field length was set as 100 m (Guo et al., 2013).

3.1.3. N leaching module

The soil N in farmland may be affected by biological factors, climatic factors, and agricultural practices, such as fertilization, irrigation, and tillage. Spatial migration and transformation of soil N often occurs, including N leaching by surface runoff and lateral subsurface flow, $\text{NO}_3\text{-N}$ transport by soil water evaporation, organic N transport by sediment denitrification, denitrification, and crop N uptake (Sharpley and Williams, 1990). Among these processes, N leaching is the primary mechanism leading to the loss of soil N, and is mainly induced by precipitation and irrigation (Klein et al., 2013). In the EPIC model, N leaching is estimated by calculating the change in the $\text{NO}_3\text{-N}$ concentration when water flows through a soil layer, as shown in Eq. (8):

$$QNO_3 = QT \cdot CNO_3 \quad (8)$$

where QNO_3 is the amount of $\text{NO}_3\text{-N}$ lost, QT represents the percolation of water volume, and CNO_3 is the average concentration of $\text{NO}_3\text{-N}$ in the specific soil layer.

3.2. Data sources

The datasets used in this paper are listed in Table 1. Crop cultivated areas of wheat, maize, and rice in 1980, 1990, 2000, and 2010 were derived from the Institute of Agricultural Resources and Regional Planning, CAAS (Liu et al., 2015). This data set consists of the crop cultivated areas and crop area in each grid with a resolution of 10×10 km. Based on the availability of crop distribution data, we used the data in 1980, 1990, 2000, and 2010 to represent the crop cultivated structure for 1980–1985, 1986–1995, 1996–2005, and 2006–2010, respectively. To represent the percentage area equipped for irrigation in each grid, a map of irrigated areas was obtained from the FAO with a resolution of 10 km (Siebert et al., 2013). General parameters of soil and soil profile properties with a 10-km resolution were derived from the Cold and Arid Regions Sciences Data Center at Lanzhou. The digital elevation model (DEM) and terrain slope data (90 m), which represent the elevations and slope of each grid, respectively, were resampled to 10 km to match other data.

In the EPIC model, the climatic variables of solar radiation, precipitation, maximum temperature, minimum temperature, wind speed, and relative humidity have been proved to be the major variables that may have significant effects on crop yield, N leaching and soil erosion (Putman et al., 1988; Wang et al., 2012; Williams et al., 2006). In this study, we mainly chose the mentioned six variables to study their impacts on the AES. Daily climatic variables of solar radiation, precipitation, $T_{\min}$, $T_{\max}$, relative humidity, and wind speed, which were required to run the EPIC model, were obtained from the China Meteorological Administration (CMA), and were interpolated to 10×10 km to ensure uniform resolution. The sown dates and harvest dates for a specific crop within a municipal area were acquired from the nearest agrometeorological station, and the growing season for wheat, maize, and rice was March to October.

The rate of fertilizer application from 1980 to 2010 was acquired from the Provincial Statistical Yearbook. Due to the lack of statistical data in each grid, we assumed that the rate of fertilizer application was homogenous within each statistical municipal area. The statistical yields of wheat, maize, and rice represented the average yield of a municipal area and were used to validate the crop model.

Due to the lack of an irrigation schedule during the period 1980–2010, we used the auto-irrigation option for the irrigated areas which was proved to be rational (Liu et al., 2007), while other areas were under rain-fed conditions.

3.3. Contribution of driving factors to the variation in AES

To quantify the predominant factors with the largest effects on crop production, soil erosion, and N leaching, the contribution of the climatic variables (solar radiation, precipitation, $T_{\min}$, $T_{\max}$, wind speed, and relative humidity) and management factors (irrigation, fertilization, and crop area) were evaluated in this study. In order to avoid collinearity between the driving factors, a partial least squares regression model was used.

To a grid, the relationship between agricultural ecosystem service and driving factors can be expressed as the following multiple linear regression equation:

$$P = a_1X_{1,t} + a_2X_{2,t} + a_3X_{3,t} + a_4X_{4,t} + a_5X_{5,t} + a_6X_{6,t} + a_7X_{7,t} + a_8X_{8,t} + a_9X_{9,t} \quad (9)$$

where P is the normalized sequence of crop production, soil erosion, or N leaching for wheat, maize, or rice in the period of t , t represents year serial number from 1980 to 2010, X_1 , X_2 , X_3 , X_4 , X_5 , X_6 , X_7 , X_8 , and X_9 are the normalized sequences of solar radiation, precipitation, $T_{\min}$, $T_{\max}$, wind speed, relative humidity, fertilizer application rate, irrigation water amount, and crop area, respectively, and a_1 , a_2 , a_3 , a_4 , a_5 , a_6 , a_7 , a_8 , and a_9 represent the regression coefficient of each driving factor. Then

$$T^2 = a_1r_1 + a_2r_2 + a_3r_3 + a_4r_4 + a_5r_5 + a_6r_6 + a_7r_7 + a_8r_8 + a_9r_9 \quad (10)$$

where T is the multiple correlation coefficient, r_1 , r_2 , r_3 , r_4 , r_5 , r_6 , r_7 , r_8 , and r_9 represent the partial correlation coefficients of crop production, soil erosion, or N leaching with the corresponding climatic or management factor, and a_1r_1 , a_2r_2 , a_3r_3 , a_4r_4 , a_5r_5 , a_6r_6 , a_7r_7 , a_8r_8 , and a_9r_9 represent the individual contribution of solar radiation, precipitation, $T_{\min}$, $T_{\max}$, wind speed, relative humidity, fertilization, irrigation, and crop area to variations in crop yield, N leaching, and soil erosion, respectively.

4. Results

4.1. Performance of the EPIC model for simulating crop yield

We used the statistical yield for each municipal area from 2001 to 2010 to evaluate the performance of the EPIC model. In order to compare the consistency of the statistical yield with the simulated yield of wheat, maize, and rice, the RMSE, RRMSE, linear regression model, and R^2 were calculated (Fig. 2). The results indicated that the simulated yield agreed well with the statistical yield. The RMSEs for wheat, maize, and rice were $<1.1 \text{ t ha}^{-1}$ in all cases; for wheat, the RMSE was even $<0.7 \text{ t ha}^{-1}$. The fitting R^2 for wheat, maize, and rice was higher than 0.6 in all cases. Overall, the model performance was robust for simulating the crop yields of wheat, maize, and rice.

4.2. The change trend of the driving factors

Variation in the driving factors for the crop cultivated areas from 1980 to 2010 is shown in Fig. 3. The results indicated that the climatic variable of solar radiation had no obvious changes (Fig. 3a) in wheat, maize, and rice during the growing season. Precipitation exhibited a slight downward trend (Fig. 3b) for wheat ($-0.274 \text{ mm} \cdot \text{yr}^{-1}$; $p = 0.49$), maize ($-0.767 \text{ mm} \cdot \text{yr}^{-1}$; $p = 0.47$), and rice ($-0.847 \text{ mm} \cdot \text{yr}^{-1}$; $p = 0.43$). Compared with the climatic variables of solar radiation and precipitation, there were significant increases in both $T_{\min}$ and $T_{\max}$ from 1980 to 2010 (Fig. 3c and d), indicating a continuous warming trend for the crop cultivated areas in the APTZ. Wind speed and relative humidity both

Table 1
Data used in this study.

Datasets	Datasets description	Source
Climate data	Daily precipitation, relative humidity, mean wind velocity, solar radiation, maximum temperature and minimum temperature (1980–2010)	China meteorological administration (http://data.cma.cn/)
Agrometeorological data	Planting and harvest dates (1980–2010)	China meteorological administration (Fischer et al., 2008)
Soil data	General parameters of soil and soil profile properties	Geospatial Data Cloud, Computer Network Information Center, Chinese Academy of Sciences (Siebert et al., 2013)
Dem and slope	Digital elevation model and terrain slope	Provincial Statistical Yearbook (Liu et al., 2015)
Irrigated area data	Map of farmland irrigation areas in 2005	Provincial Statistical Yearbook
Fertilizer application	Fertilizer application rates from 1980 to 2010	Provincial Statistical Yearbook
Geographic distribution of major crops	Spatial distribution of wheat, maize and rice in 1980, 1990, 2000, 2010	Provincial Statistical Yearbook
Crop yields of statistical data	Statistical yields of wheat, maize and rice from 2001 to 2010	Provincial Statistical Yearbook

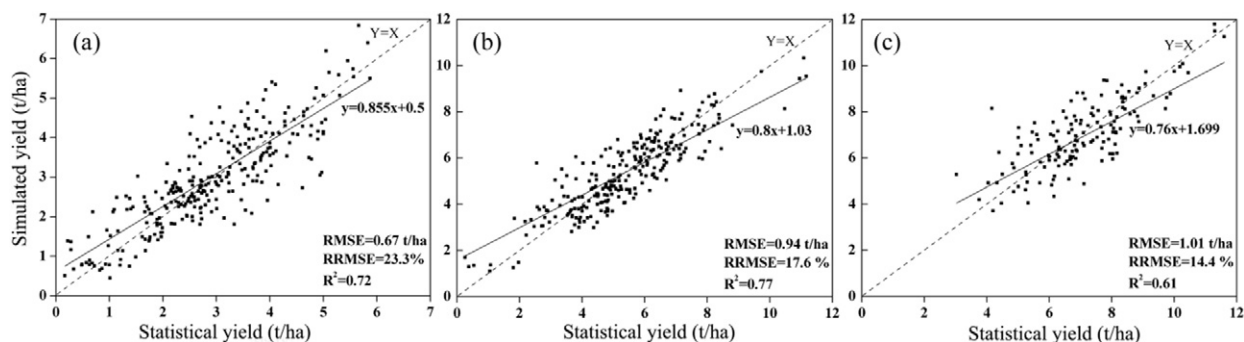


Fig. 2. Comparison between statistical yield and simulated yield and the sampling points for wheat (a), maize (b), and rice (c) are 274, 254, and 146, respectively.

exhibited a downward trend for the crop cultivated areas (Fig. 3e and f). There was a significant increasing trend for fertilizer application rate on wheat ($8.98 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$; $p < 0.01$), maize ($9.138 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$; $p < 0.01$), and rice ($8.8 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$; $p < 0.01$) (Fig. 3g). In 1980, the fertilizer application rate for the three crops was $< 100 \text{ kg ha}^{-1}$, subsequently increasing more than three times, and was nearly 300 kg ha^{-1} in 2010. The regional mean amount of irrigation water in irrigated areas exhibited a decreasing trend for wheat ($-0.072 \text{ mm} \cdot \text{yr}^{-1}$; $p = 0.75$) and increased trends for maize ($4.579 \text{ mm} \cdot \text{yr}^{-1}$; $p < 0.01$) and rice ($2.437 \text{ mm} \cdot \text{yr}^{-1}$; $p < 0.05$) (Fig. 3h). There were notable differences in the cultivated areas of wheat, maize, and rice (Fig. 3i). The cultivated area of wheat decreased ($-3.26 \times 10^4 \text{ ha} \cdot \text{yr}^{-1}$; $p < 0.01$), while that of maize increase ($1.03 \times 10^5 \text{ ha} \cdot \text{yr}^{-1}$; $p < 0.01$). There was no obvious change in the rice cultivated area ($20.16 \text{ ha} \cdot \text{yr}^{-1}$; $p = 0.99$) from 1980 to 2010.

4.3. Changes in the AES

Fig. 4 shows there were obvious changes in crop production, soil erosion, and N leaching. Overall, the total crop production ($3 \times 10^6 \text{ t}$; $p < 0.01$) and N leaching ($0.27 \times 10^{-2} \text{ t}$; $p < 0.01$) exhibited a significantly increased trend, whereas the soil erosion declined (-0.13 t ; $p = 0.1$) during the period of 1980 to 2010 in the APTZ (Table 2). The crop production in most crop cultivated areas (72.9%) tended to increase, with the northeast identified as a hotspot of increasing crop production, reaching $1.78 \times 10^3 \text{ t} \cdot \text{yr}^{-1}$. Areas in which crop production followed a decreasing trend were small and mainly found in the southwestern region (Fig. 4a). On the contrary, nearly 56.9% of the areas experienced a declining trend for soil erosion. Areas in which soil erosion dramatically decreased were mainly in the northeast and south-west of the APTZ (Fig. 4b). Most areas (73.1%) exhibited an increasing

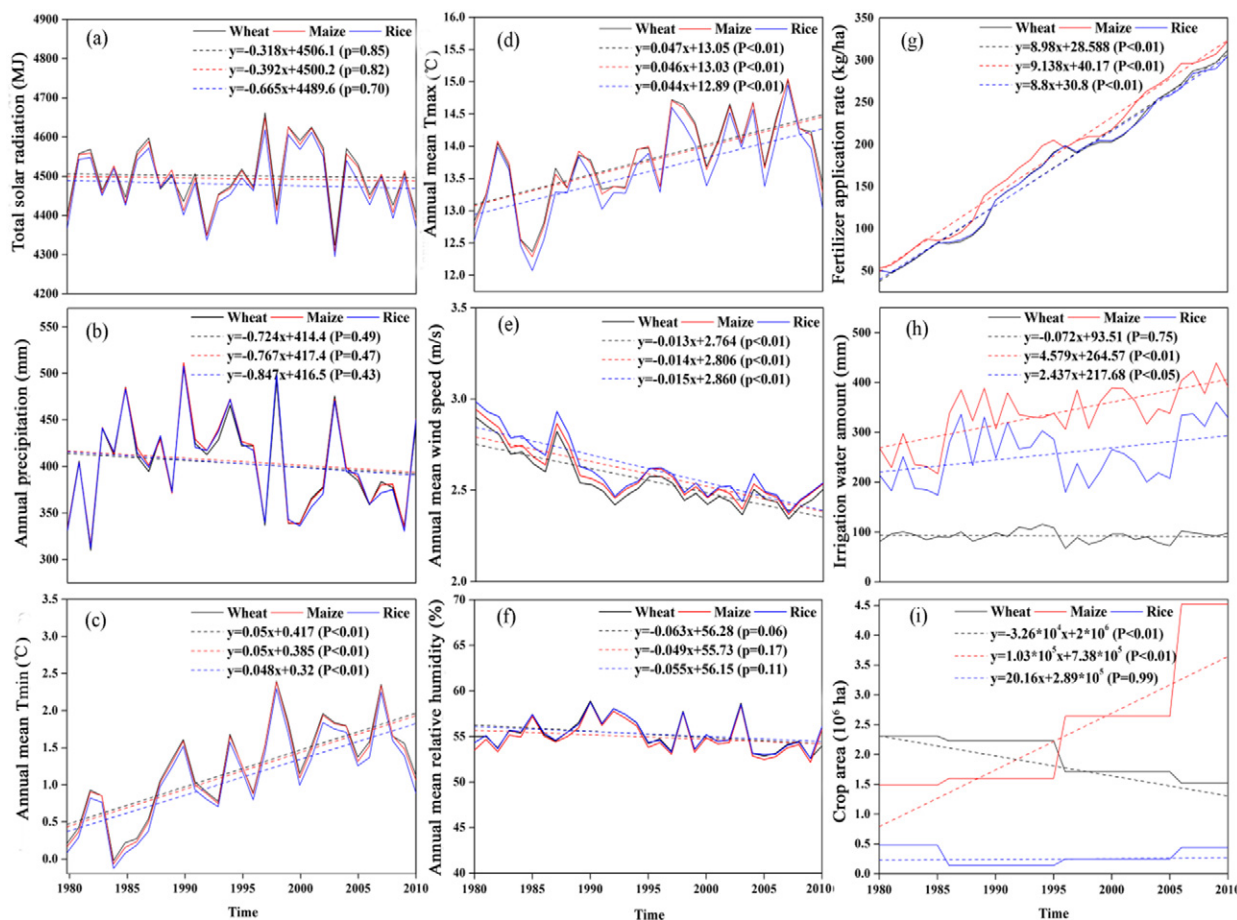


Fig. 3. Changes in driving factors from 1980 to 2010 for the crop cultivated areas. The climatic factors are (a) annual total solar radiation, (b) annual precipitation, (c) annual mean $T_{\min}$, (d) annual mean $T_{\max}$, (e) annual mean wind speed, and (f) annual mean relative humidity during the growing season; (g) fertilizer application rate, (h) irrigation water amount, (i) crop area.

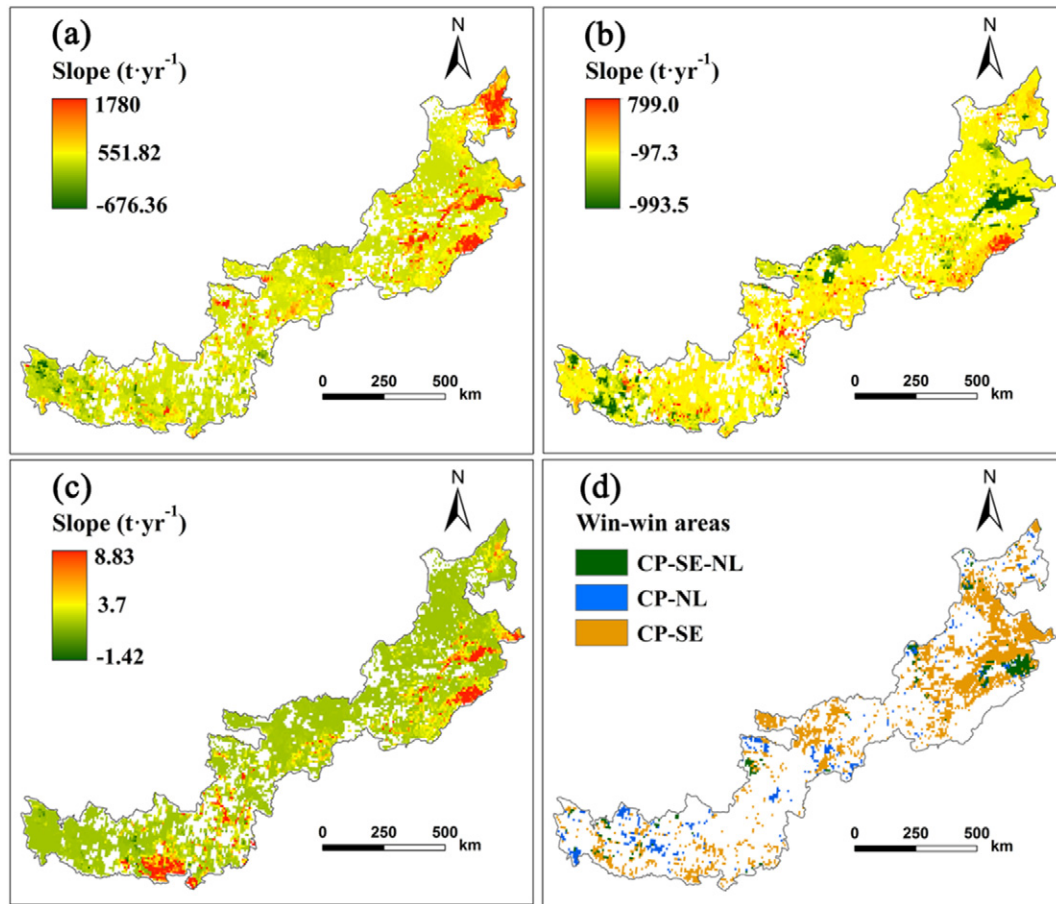


Fig. 4. Spatial patterns of linear trends in crop production (a), soil erosion (b), and N leaching (c), and win-win areas for the three AES (d) in the APTZ from 1980 to 2010. Notes: CP represents crop production, SE represents soil erosion, and NL represents N leaching. CP-SE-NL: crop production increased while soil erosion and N leaching decreased; CP-NL: crop production increased while N leaching decreased; CP-SE: crop production increased while soil erosion decreased.

trend for N leaching, with these changes exhibiting low spatial heterogeneity. The hotspots of areas with increased leaching were relatively concentrated and mainly distributed in the northeast and southwest of the APTZ (Fig. 4c). Our study indicated that the areas with increased crop production while decreased soil erosion and N leaching were existed and primary distributed in the small areas of northeast. The win-win areas with increased crop production and decreased soil erosion were concentrated in the northeast whereas the win-win areas for crop production and N leaching were mainly scattered in the southwest (Fig. 4d).

4.4. Effects of driving forces on the AES

4.4.1. Effects of driving forces on crop production

From 1980 to 2010, the regional mean contributions of total climatic factors (Tcf) to variation in the production of wheat, maize, and rice were 15.36, 12.39, and 11.54%, respectively (Fig. 5d). Among the climatic variables of solar radiation, precipitation, $T_{\min}$, $T_{\max}$, wind speed, and relative humidity, $T_{\min}$ had largest effect on crop production, and the contributions on wheat, maize, and rice were 4.2, 3.72, and 2.53%,

respectively (Fig. 5a). The rates of regional mean contribution of the total factors, including Tcf, fertilization, irrigation, and crop area, to the production variation of wheat, maize, and rice were 85.78, 93.48, and 94.1%, respectively (Fig. 5d). For wheat, maize, and rice, the primary driving factor affecting crop yield was crop cultivated area. Compared with Tcf, irrigation, and crop area, fertilization contributed the least to the variation in crop production for wheat (4.69%), maize (8.96%), and rice (7.78%).

Regarding the spatial contribution of climatic variables to variation in the production of wheat, maize, and rice, areas with a high contribution (red color) of solar radiation, precipitation, $T_{\min}$, and $T_{\max}$, wind speed, and relative humidity were small and scattered throughout the whole region (Fig. S1). Areas where fertilization had a high contribution for wheat were relatively concentrated in the southwest, and were primarily distributed in the northeast for maize and rice. The contribution of the crop cultivated area was higher than that of other driving factors for wheat, maize, and rice in most areas (Fig. S4 a4, b4, c4).

4.4.2. Effects of driving forces on soil erosion

During the study period, the regional mean contributions of total factors to variation in soil erosion for wheat, maize, and rice were 54.2, 62.8, and 55.7%, respectively. Compared with the climatic variables of solar radiation, precipitation, $T_{\max}$, wind speed, and relative humidity, $T_{\min}$ was the primary factor affecting soil erosion. The rates of $T_{\min}$ contribution to the variation in soil erosion for wheat, maize, and rice were 6.2, 5.63, and 5.36%, respectively (Fig. 5b). Among the driving factors of Tcf, fertilization, irrigation, and crop area, crop area had the greatest effect on the soil erosion of maize and rice, except for wheat cultivated

Table 2
Variation of agricultural ecosystem services simulated by the EPIC model in the APTZ during 1980–2010.

Agricultural ecosystem services	Minimum (10^6 t)	Maximum (10^6 t)	Standard deviation (10^6 t)	Slope of linear trend (10^6 t)
Crop production	5.26	26.15	7.03	3
Soil erosion	4.87	16.99	3.85	−0.13
N leaching	0.2×10^{-2}	8.9×10^{-2}	2.76×10^{-2}	0.27×10^{-2}

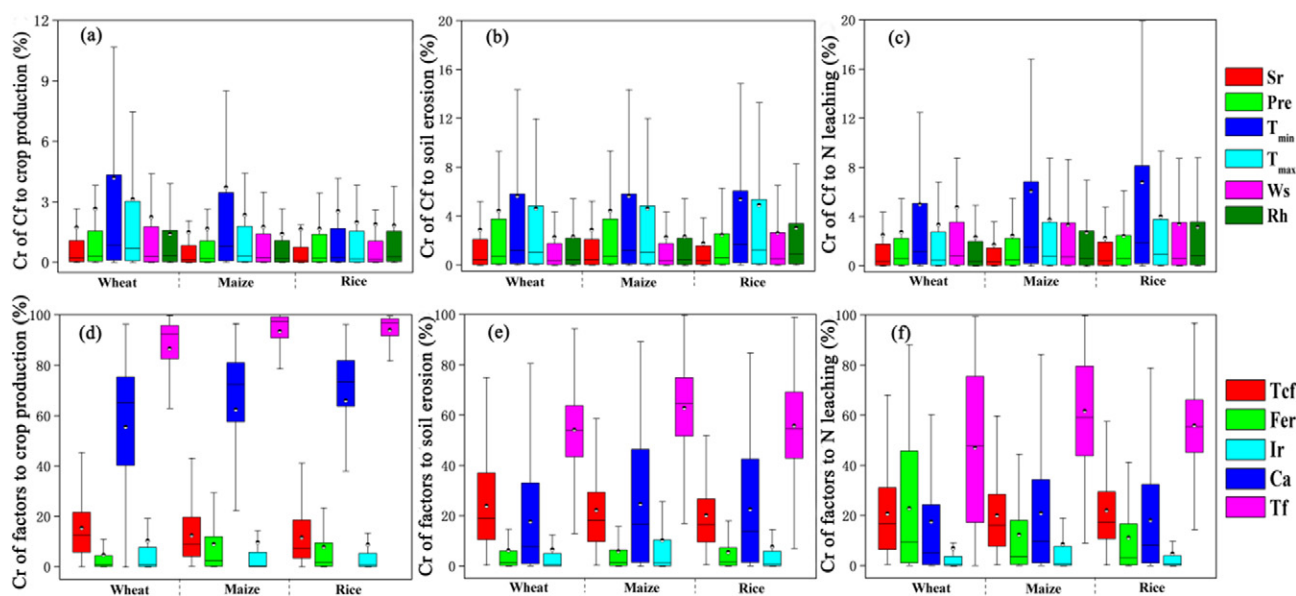


Fig. 5. Regional mean contribution rates (Cr) of climate factors (Cf) (solar radiation (Sr), precipitation (Pre), minimum temperature ($T_{\min}$), maximum temperature ($T_{\max}$), wind speed (Ws), and relative humidity (Rh)) to the variation of (a) crop production, (b) soil erosion, and (c) N leaching and total climatic factors (Tcf), management factors (fertilization (Fer), irrigation (Ir), crop area (Ca), and total factors (Tf)) to the variation of (d) crop production, (e) soil erosion, and (f) N leaching for wheat, maize, and rice in the APTZ from 1980 to 2010.

areas where climate factors were the primary influence on soil erosion (Fig. 5e). In space, the distribution of high contribution areas (red color) for all driving forces followed no obvious patterns and were scattered throughout the whole region (Figs. S2, S5). Comparatively, the crop area was the factor with the highest contribution for most crop cultivated areas of wheat, maize, and rice (Fig. S5 a4, b4, c4).

4.4.3. Effects of driving forces on N leaching

In the APTZ, the regional mean contributions of total factors to variation in N leaching for wheat, maize, and rice were 47.1, 62.0, and 55.8%, respectively. The primary driving forces with the largest effects on N leaching for wheat, maize, and rice were fertilization, crop area, and Tcf, with contributions of 22.8, 20.9, and 21.9%, respectively, during the study period (Fig. 5f). Among the climatic variables of solar radiation, precipitation, $T_{\min}$, $T_{\max}$, wind speed, and relative humidity, $T_{\min}$ was the most important variable affecting N leaching for the three crops (Fig. 5c). Regarding the spatial contributions of driving factors to N leaching, the high value areas (red color) for Tcf, irrigation, and crop area were spread across the whole region (Figs. S3, S6). However, regarding the effect of fertilizer on N leaching, areas of high contribution were clustered in the northeast of the APTZ for wheat, maize, and rice (Fig. S6 a2, b2, c2).

4.5. Predominant factors affecting the AES

In the APTZ, the predominant factor affecting crop production was crop area, which accounted for 80.9, 83.4, and 86.9% of changes in crop production for wheat, maize, and rice, respectively (Figs. 6–7). With the exception of crop area, the dominant affected areas for irrigation on crop production were mainly occurred in the northeast and southwest (Fig. 6). Compared with crop production, the predominant factors affecting soil erosion exhibited higher spatial heterogeneity (Fig. 6). With the exception of crop area and Tcf, fertilization and irrigation were also important dominant factors in soil erosion, and accounted for at least 8.25% of the crop cultivated areas (Fig. 7). The dominant driving forces that led to variation in N leaching for wheat, maize, and rice areas were fertilization (40.1%), crop area (38%), and crop area (42%), respectively (Fig. 7). The N leaching in wheat cultivated areas tended to be affected by fertilization and crop area. Changes in

crop area and Tcf were the predominant factors influencing N leaching for most cultivated areas of maize and rice.

5. Discussion

5.1. Impacts of climatic and management factors on the AES

Changes in climatic factors in the APTZ during the study period were quite large, particularly the $T_{\min}$ and $T_{\max}$, which increased significantly. This obvious warming trend was consistent with previous records (Hao et al., 2017a; Lu et al., 2009; Zhang et al., 2011). Many studies have shown that crop production would increase due to extended growing seasons under climate warming (Xiong et al., 2007). However, the findings of other studies indicated that the increased temperature would accelerate crop growth and lead to a decline in the grain-filling duration (Tao et al., 2008). Overall, the warming trend had either a positive or a negative effect on crop production, depending on the regional climate regime and crop resistance. When the daily air temperature is lower than the base temperature for crop growth, the crop growth would be restrained; on the contrary, climate warming would decrease temperature stress and increase crop production. When the daily air temperature is higher than the optimum temperature for crop growth, climate warming would increase temperature stress and decrease crop production (Sharpley and Williams, 1990). In our study area, the climate is characterized as dry and cold, such that precipitation and temperature were the most important limiting factors on vegetation growth. The temperature was notably increased (Fig. 3c and d), while changes in precipitation (Fig. 3b) were relatively small from 1980 to 2010. Compared with other climatic variables, the temperature had the greatest effect on the variation in crop production for wheat (7.32%), maize (6.1%), and rice (4.5%) in the APTZ (Fig. 5a, b, c), which was consistent with the results of Tao et al. (2008). During the study period, the number of days under temperature stress was slightly increased for maize and rice, but not for wheat (Fig. 8). This indicated that the temperature variation was beneficial for wheat production, but negative for maize and rice. In addition, the marked increase in temperature led to a decrease in soil surface moisture and thus facilitated soil wind erosion. N uptakes for crop growth, N leaching by water flow, and $\text{NO}_3\text{-N}$ transport by soil water evaporation are important processes for the migration and transformation of soil N. By influencing crop growth and soil water evaporation,

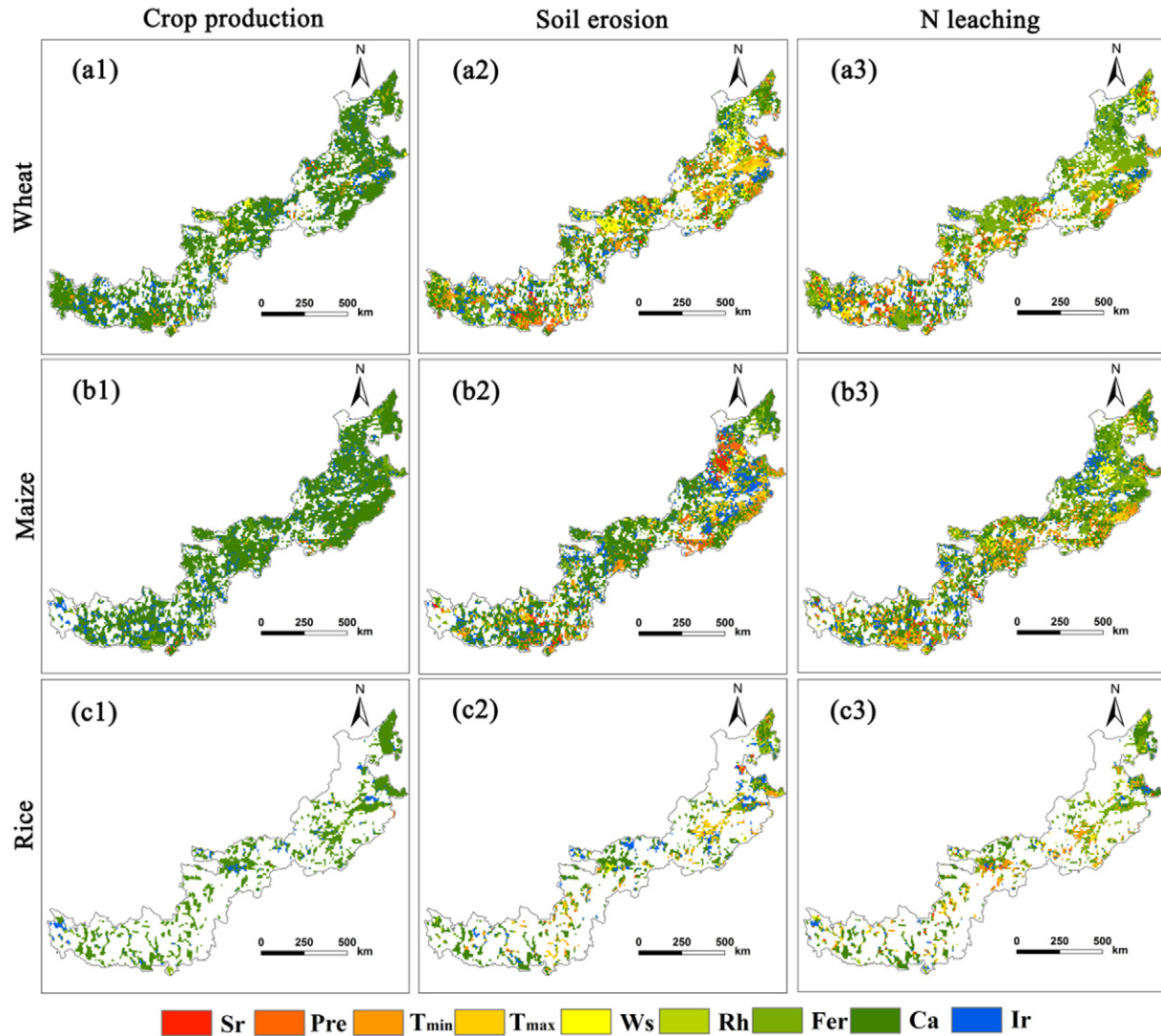


Fig. 6. Predominant factors (solar radiation (Sr), precipitation (Pre), minimum temperature ($T_{\min}$), maximum temperature ($T_{\max}$), wind speed (Ws), relative humidity (Rh), fertilization (Fer), crop area (Ca), and irrigation (Ir)) affecting the agricultural ecosystem services for wheat, maize, and rice in the APTZ from 1980 to 2010. The predominant factors were identified from the contribution rates of individual climatic factor to variations in crop yield, soil erosion, and N leaching for wheat, maize, and rice from 1980 to 2010 (presented in the Supplementary Figs. S1–S3), and the contribution rates of total climatic factors and individual management factor to variations in crop yield, soil erosion, and N leaching for wheat, maize, and rice from 1980 to 2010 (presented in the Supplementary Figs. S4–S6).

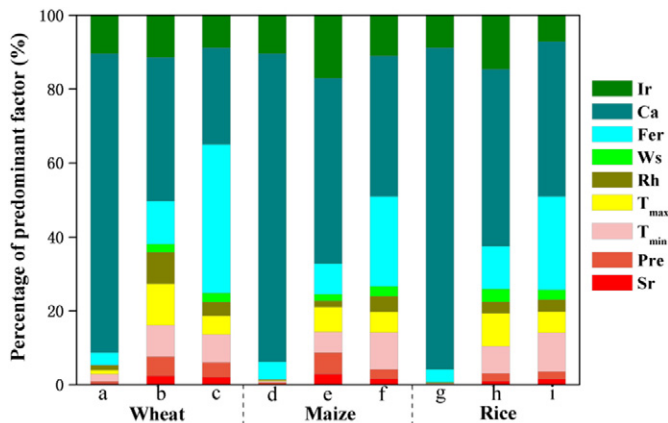


Fig. 7. Area percentage of predominant factors [solar radiation (Sr), precipitation (Pre), minimum temperature ($T_{\min}$), maximum temperature ($T_{\max}$), wind speed (Ws), relative humidity (Rh), fertilization (Fer), crop area (Ca), and irrigation (Ir)] affecting crop production (a, d, g), soil erosion (b, e, h), and N leaching (c, f, i) in the cultivated areas of wheat, maize, and rice from 1980 to 2010.

temperature indirectly affects N leaching. Thus, changes in temperature also affect N leaching.

In the arid and semiarid APTZ, water shortage is severe and moisture is a critical limiting factor for vegetation growth (Hao et al., 2017b). When the plant water-use rate is lower than the potential water-use rate, water stress occurs. From 1980 to 2010, the precipitation in this region declined somewhat (Fig. 3b), which was consistent with the report of Gong et al. (2004), and increased water stress. Although irrigation could reduce water stress, the irrigated areas were very limited (Fig. 1). Consequently, the number of days under water stress increased for wheat, maize, and rice from 1980 to 2010 in the APTZ (Fig. 8), which exerted negative effects on crop production. The findings of our study indicated that the total contributions of both precipitation and irrigation to the variation in crop production for wheat, maize, and rice exceeded 10%. Although precipitation and irrigation can lead to soil erosion (water erosion) and N leaching, they were not the predominant factors in the study region. On one hand, the average annual precipitation in our study area is 399.37 mm during 1980–2010, and precipitation mainly occurred in summer when the crop growth and soil surface cover were optimal (low CE in Eq. (7)), making water erosion less occurring. On the other hand, there was minimal N leaching due to the limited

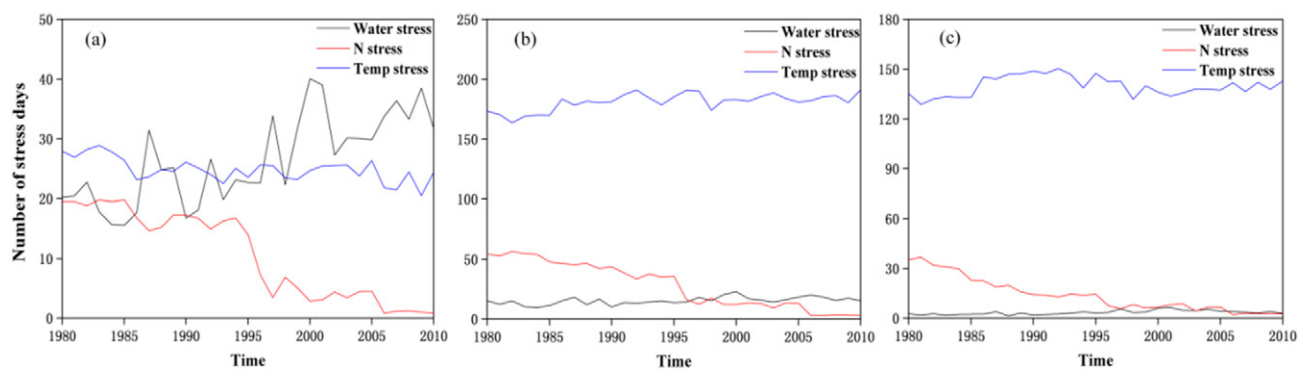


Fig. 8. Days of water, nitrogen (N), and temperature (Temp) stress for wheat (a), maize (b), and rice (c) during the growing season.

irrigation facilities. In this case, the regional mean contribution of irrigation to the variation of N leaching was little. It should be noted that the crop planting areas of wheat, maize, and rice were mainly distributed in the northeast and southwest region where irrigation conditions were relatively good. Therefore, irrigation had larger effects on N leaching in the northeast and southwest regions as indicated in Fig. 6a3, b3, c3.

The input of nutrients from fertilization could supply the necessary elements (i.e., N) for crop growth, and thus enable progress in crop production. During the growth process of the crops, when the soil N content was lower than that needed for crop growth, N stress would occur and limit the crop growth (Walburg et al., 1982). In the present study, the rate of fertilizer application had a marked increase, which accompanied local economic development (Fig. 3g). As a result, the number of days spent under N stress declined for wheat, maize, and rice during growing seasons (Fig. 8), and increased crop production was promoted in the APTZ from 1980 to 2010. By 2010, N stress days were close to zero and N was no longer a major limiting factor for crop yields. The further increase of fertilizer inputs will not have a positive effect on crop yield. On the contrary, excessive fertilizer may lead to the soil deterioration and decrease in crop yield (Ju et al., 2007; Tilman et al., 2011; Vitousek et al., 2009). It should be noted that fertilization could also indirectly affect soil erosion by improving the crop growing conditions and vegetation cover on the soil surface. In this way, soil erosion was restrained with increased fertilizer application. Fertilization was also a critical driving factor (reaching 22.8% for wheat) for variation in N leaching, by directly changing the soil N-NO₃ concentration. Yang et al. (2015) reported similar findings, with a significant positive correlation observed between N leaching and N fertilizer rates.

Agricultural land-use changed significantly in the APTZ during the study period, particularly for the crop shares of wheat, maize, and rice (Fig. 3i). On one hand, agricultural policy adjustments and human activities (i.e., the Grain for Green project, urbanization) led to changes in farmland area (Wu et al., 2015). Conversely, climate change led to variation in suitable crop cultivated areas and moved the northern limit for crop growth (Shi et al., 2014). Due to the effects of the aforementioned factors, the crop cultivated areas of maize and rice in the APTZ increased dramatically, whereas that of wheat decreased by 1.52×10^6 ha from 1980 to 2010. Such marked changes in the crop area directly resulted in variation in AES, and thus contributed greatly to the variation in crop production (>55.5%), soil erosion (>17.6%), and N leaching (>17.4%) for wheat, maize, and rice, respectively.

5.2. Implications for AES management

Our study found that climatic and management factors had significant effects on the AES. Changes in the crop area played a predominant role in crop production for >80% of the crop cultivated area of wheat, maize, and rice, and led to an increase in maize and rice production from 1980 to 2010. However, the decreased wheat cultivated area was the main reason for the decline in wheat production. Therefore,

adjustment of the crop cultivated area and structure are measures of adaptation to climate change. Furthermore, irrigation conditions were also predominant factors affecting the crop production of wheat, maize, and rice. Irrigation had obvious effects on crop production due to the lack of water in the arid and semiarid study area. Therefore, the development and investment of irrigation facilities could increase crop production. Climate change exerts great effects on crop production, particularly for T_{min}, which had the largest contributions on wheat, maize, and rice. As a result, measures such as covering the soil surface with plastic film to improve surface temperature can be used to reduce the negative influence of T_{min}.

Irrigation was a dominant factor influencing soil erosion, and account for >10% of crop cultivated areas. In this region, the irrigated areas were primarily distributed in the northeast where the soil types were mainly sand and loamy sand (Fig. 1e). The soil erodibility factor (k in Eq. (7)) of these soil types is high, and easily results in soil loss (Morgan, 2009). Therefore, drip irrigation, rather than flooding irrigation, should be adopted to reduce soil loss and improve water utility rate.

Fertilization was a dominant factor for >24% of crop cultivated areas, and most importantly affected N leaching, which was dependent on the concentration of N-NO₃ and the volume of water runoff. The results indicated that reducing the rate of fertilizer application can reduce N leaching for the dominant areas of fertilization (Fig. 6a3, b3, c3). However, it should be noted that reducing the rate of fertilizer application would also decrease crop production. Generally, there may be an obvious tradeoff between crop production and N leaching. However, in our study, possible compromises between crop production and N leaching were identified, with increased crop production and decreased N leaching in some areas (Fig. 4). Fang et al. (2006) and Yang et al. (2015) also proved that with controlled irrigation and matched N inputs, crop production was sustained while N leaching decreased. Further study is needed to optimize the AES with proper management practices.

6. Conclusions

We investigated the effects of climatic and management factors on the AES in terms of crop production, soil erosion, and N leaching in the APTZ from 1980 to 2010 using the GIS-based EPIC model and a partial least squares regression model. Our simulated results indicated that the total crop production and N leaching exhibited a significantly increased trend, whereas soil erosion declined in the APTZ. Climatic variables and management factors (fertilization, irrigation, and crop area) could well explain the changes in the AES. Besides the changes in the cultivated area, climate change also played important roles in the variations of crop production and soil erosion. Fertilization was a major factor and accounted for >11.1% changes in N leaching.

The results of our study suggested that, although tradeoffs existed between increasing crop production and negative environmental

effects, synergy can be achieved through application of plastic film, drip irrigation and optimal fertilizer application rate. This study improves our understanding of how climatic and human management factors affect the AES. This approach could be applied in other agricultural regions for promoting crop production while reducing negative environmental impacts under climate change.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.scitotenv.2017.08.264>.

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